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Ecosystem Services in a Simple Macroeconomic Framework

Björn Döhring, loanna Grammatikopoulou, Alessandra La Notte, Beatrice Pataracchia, Domenico Pisani, Christophe Planas, Josselin Roman, Alessandro Rossi, Anna Thum-Thysen, Mayra Nucci Zurbaran

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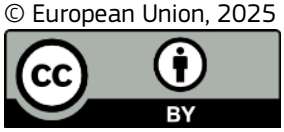

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Abstract

Economic activity is exerting increasing pressure on natural ecosystems while it depends at the same time on the provision of the services that these ecosystems provide. In this paper, we build on the conceptualisation of ecosystem services in the statistical framework developed by the United Nations, namely the System of Environmental-Economics Accounting - Ecosystem Accounting (SEEA EA). We use a simple aggregate production function augmented with the direct and indirect contribution of ecosystem services to illustrate the dependence of economic activity in EU Member States on forest ecosystem assets. Simulating the degradation of ecosystems 25 and 60 years ahead, we show that the negative impact on economic activity in the EU could be sizeable. This is particularly so when we assume that fixed capital and labour cannot easily substitute for the loss of forest assets. While our analysis is limited to one type of ecosystem and our quantification purely illustrative, our framework serves as a proof of concept for tools that could usefully inform macroeconomic policy decisions for the medium term.

JEL Classification: 057, E01, E23.

Keywords: forest ecosystem services, natural capital, potential output.

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Contact: loanna Grammatikopoulou, ioanna.grammatikoupoulou@ec.europa.eu, European Commission, Joint Research Centre, Björn Döhring, bjoern.doehring@ec.europa.eu, European Commission, Directorate-General for Economic and Financial Affairs.

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1. INTRODUCTION

The depletion and degradation of natural capital is set to increasingly affect future economic possibilities. This is already happening: Having emitted greenhouse gases persistently beyond the natural absorption capacity of ecosystems globally since the industrial revolution, we are now faced with an increase in the frequency of natural disasters, which further weakens ecosystems' capacity to provide critical services.

Although classical economists considered land as a production factor, and the concept of 'natural capital' has been employed in environmental economics for decades, standard contemporary macroeconomic models continue to abstract from the interactions between natural assets and the economy (for a discussion, see for example Dasgupta (2021) or Lange et al. (2018)). As the sustainability of economic activity has become a more obvious concern for economic policy makers, it is more and more pressing to reflect the interaction between economic activity and nature in the modelling tools used for economic policy advice.

In the past, macroeconomic modelers and macroeconomists advising policymakers have generally shown limited interest in natural capital accounting, but this is changing rapidly. Recent policy initiatives and discussions on the economic importance of natural capital include the OECD (2021), the World Bank (Johnson et al. (2021), the Coalition of Finance Ministers for Climate Action (Power et al. (2022)), Monetary Policy makers (e.g. Boldrini et al. (2023), NGFS (2023)) and the White House (2023).

Against the background of increasing ecological concerns, efforts have been stepped up to better measure the contribution of natural assets to the economy and the impact of the economy on the natural environment. Environmental economic accounts aim at understanding the contributions of nature to economic processes and reflect them in data that are compatible with national accounts. Nonetheless, at present, these data cover only a subset of the relevant ecosystems and ecosystem services. This invites the question what can be said already today about the dependence of the economy on natural inputs from the perspective of macroeconomic models.

In this paper, we explore the contribution of ecosystem services to the economy first conceptually and then quantitatively. Typically, a particular ecosystem provides several types of ecosystem services, and economic activities benefit from services provided by several different ecosystems. For our quantitative exploration, we focus on forests and the ecosystem services they provide. We feed ecosystem services data into a model that serves to project potential economic output over the medium term, as an extension of current tools underpinning

macroeconomic surveillance. Concretely, we use forest ecosystem services to demonstrate the suitability of an aggregate macroeconomic production function extended to natural capital for studying the dependence of the economy on natural assets. We use this framework to simulate different paths for the future dynamics of forest ecosystems to assess how these would impact economic production possibilities in the future. As we are particularly interested in the consequences of substitutability between natural and man-made inputs, we extend the production function suggested by Dasgupta (2021) to simulate different elasticities of substitution.

We use ecosystem services data from the World Bank and the European Commission and find that adding ecosystem services into our production function framework modifies total factor productivity (the estimated Solow residual). In most EU Member States, forests contribute positively to economic production. The two datasets yield quantitatively similar results overall, though the distribution across Member States differs somewhat. When we simulate the medium- and long-term impact of declining ecosystem services, we find sizeable impacts. Even in a scenario with the increase of global mean temperature contained well below 2 degrees Celsius, the degradation of forest ecosystems in the EU would shave 0.7 % off EU GDP by 2085. If we include global ecosystem services, i.e. provided by the World Bank at global scale, the damage would triple. Assuming on top that natural assets can only to a limited degree be replaced by fixed assets or labour, the impacts could become much larger.

Our paper relates to different strands of the literature. A first one covers the data and methodologies for measuring natural assets and ecosystem services. In the European Union, the United Nations' System of Environmental-Economic Accounting Ecosystem Accounting (SEEA EA, see UN (2014) and United Nations (2024)) is implemented through Eurostat's Environmental Economic Accounts. These frameworks allow integrating economic and environmental data using a common set of concepts, definitions, classifications and accounting rules. The EU contributed significantly to this endeavour through the Knowledge Innovation Project on Integrated Natural Capital Accounting (INCA), jointly undertaken by the European Commission and the European Environment Agency (see Vysna et al. (2021); Bagstad et al. (2021)). To date, only part of the SEEA is implemented, and work remains in progress, in particular accounting for ecosystem services. The UN handbooks cited above describe the methodologies for measuring the extent and condition of ecosystems as well as the flow of ecosystem services in physical terms and the principles and approaches for their monetary valuation. Estimations of physical flows in monetary units are necessary for the

purpose of aggregation (e.g. of different services provided by one ecosystem) and comparison (e.g. across different ecosystems). Monetary valuation is also necessary for cost-benefit analysis, wealth accounting, assessing financial risks, guiding (public) investment decisions and providing baselines for analysis and modelling (UN (2021b), p. 177). Monetary valuation thus adds transparency and analytical underpinnings to economic and political decision-making. Difficulties and caveats are e.g. discussed in Fenichel et al. (2018) and Radermacher and Steurer (2015). At the level of the EU, environmental economic accounts are available from Eurostat and ecosystem accounts more specifically in the INCA database. The World Bank has developed the "Changing Wealth of Nations" database, which covers physical, human and natural capital stocks in values for a large set of countries.

The second corpus of literature we relate to covers the modelling of natural capital in economic production. There are different possibilities for modelling the role of natural capital in economic output or wellbeing. The modeling approaches developed so far differ in terms of granularity, coverage of different types of natural assets and representation of the feedback loop between economic activity and natural capital. At a high level of detail, ecological models that describe one or several ecosystem services in their geographical context are linked to highly disaggregated economic models through input-output relationships or general equilibrium models through the assessment of gross ecosystem products (see e.g. La Notte et al. (2020); Rokicki et al. (2024)).

Some, such as Johnson et al. (2023), have an explicit feedback loop covering the economic pressures on nature and the impact of natural asset degradation on the economy. In the climate-economic literature it is standard to model the feedback loop involving greenhouse gas emissions from economic activity and the economic damages resulting from increasing temperatures at a high level of aggregation in integrated assessment models (IAMs). The extension of climate IAMs to cover natural capital more broadly is still in its infancy, e.g. Bastien-Olvera and Moore (2021) have extended a standard climate IAM with natural capital. Their model highlights the impact on the economy both directly from climate change and via the damage that rising temperatures cause to natural capital. Simpler aggregate models focus on a macroeconomic production function augmented with natural capital. Climate change and more in general the degradation of natural capital can affect all the drivers of potential output: fixed capital, labour and total factor productivity (TFP) (Parker (2023)). It has already been shown that TFP is mis-specified in a production function that does not explicitly include natural capital (Cárdenas Rodríguez et al. (2023); Thia et al. (2024)). Dasgupta (2021) suggests an extended production function in which the flow of resources and the flow of ecosystem services are made explicit. A production function specified in this way is used

and elaborated further in Bastien-Olvera et al. (2023).

Thirdly, we extend our simple production function framework to explore the effects of limited substitutability of natural capital by other assets. This extension builds on literature that highlights the difficulty of making economic production sustainable when some inputs are essential, i.e. hard to substitute. Dasgupta and Heal (1974) already stressed the link between sustainability and substitution. Limited substitutability impacts the shadow price of natural capital (Drupp et al. (2024)). In our simple exercise, we will treat the elasticity of substitution as certain and fixed, though we experiment with different values. More realistically, substitution possibilities can evolve over time (Acemoglu et al. (2012) , Hassler et al. (2021)), and the uncertainty related to future substitution possibilities affects the value of natural capital today (Gollier (2019)).

Fourth, in using quantitative scenarios for the future dynamics of natural assets, we follow a tradition going back more than 50 years to the initial Club of Rome report (Meadows et al. (1972)). The combination of qualitative and quantitative elements in scenarios or pathways is a central element in the IPCC and UNEP flagship reports (Lee et al. (2021), UN (2019)). Different approaches for using ecosystem accounts in policy scenarios are discussed in UN (2021a). Challenges in scenario-building include the complexity of natural systems, non-linear dynamics (for an overview and illustration see Dasgupta (2021) chapter 3) and the interdependencies within and across different systems (see e.g. Willcock et al. (2023)). Moreover, it is difficult to build scenarios that are macroeconomically relevant from the observation of local and specific ecosystems (NGFS (2023)). Several authors argue that worst-case scenarios should be discussed in order to design policies that act as insurance against low probability - high impact events (e.g. Kemp et al. (2022)). In this paper we follow Bastien-Olvera et al. (2023) and base our scenarios on two among the Shared Socioeconomic Pathways. Finally, our focus will be on efforts to integrate natural capital into tools for macroeconomic surveillance, in particular the models used for the estimation and projection of potential output. This approach could be integrated with existing methodologies for production function-based potential output estimation (as for example in Havik et al. (2014)) and used to underpin macroeconomic surveillance.

Our contribution to this literature consists firstly of distinguishing two paths through which ecosystem services affect economic production, namely on the one hand by provisioning services that underpin renewable resources (in our case timber) and on the other regulating and

maintenance services that enable economic activity in the first place. Such a distinction was suggested by Dasgupta (2021). We further refine this framework by making substitutability explicit and studying the effect of different assumptions about the elasticity of substitution between ecosystem services and the other input factors. Our production-function framework is close to standard methodologies for making potential output projections for macroeconomic surveillance. Our work can therefore serve as proof of concept for including the contribution of natural capital more systematically in macroeconomic surveillance.

The remainder of this paper is structured as follows: Section 2 presents the conceptual framework for the measurement of ecosystem services as defined by the UN and implemented in the EU. Section 3 describes the data we use in our quantitative analysis. The modelling framework and results of our simulations are presented in section 4. Section 5 concludes.

2. ECOSYSTEM SERVICES' DEFINITION AND CONTRIBUTION TO THE ECONOMY

The term "ecosystem services" has officially entered the scientific community thanks to the Millennium Ecosystem Assessment (MA) (Millennium Assessment (2005)), although the debate on its underpinning framework and related classifications were already in place (Costanza et al. (1997); de Groot et al. (2002)). The MA was only the starting point of an evolution that brought the meaning of "service" from its identification as a "benefit" to "ecosystem contribution" to human activities, i.e. from the benefit itself to the ecological process that generates the benefit (Haines-Young and Potschin (2018); TEEB (2010)). The difference between services and benefits is further supported by the SEEA EA (United Nations (2024)), which explicitly acknowledge the cascade framework (Haines-Young and Potschin (2012); Potschin-Young et al. (2018)) as the conceptual model underpinning the coherent accounting of ecosystem services with respect to the System of National Accounts (SNA). According to the cascade model in fact, the biophysical structure of ecosystems supports ecological functioning (such as photosynthesis, nutrient, water and carbon cycles) that in turn generate ecosystem services (such as biomass growth, water purification, flood control and carbon sequestration) that in turn provide the benefits perceived by people (wood logged, cubic meter of clean water, avoided flood damages and carbon credits).

According to the SEEA EA, several modules support a consistent provision of accounting relevant ecosystem-related data (Figure 1).

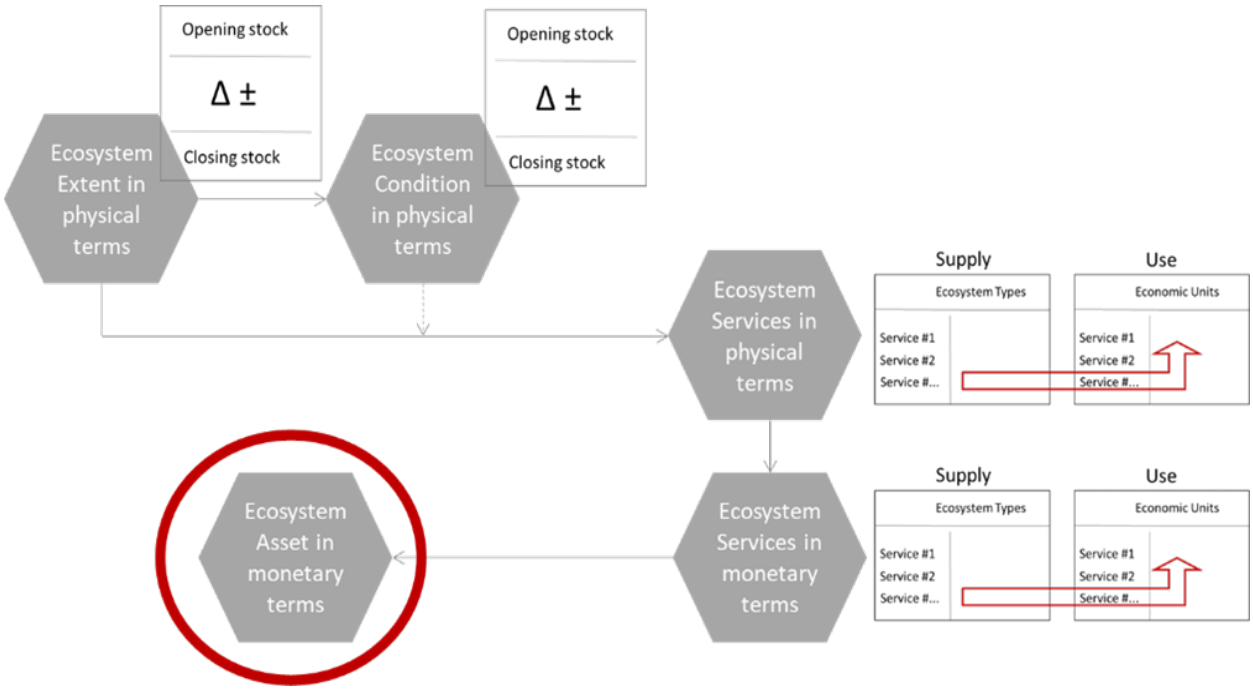


Figure 1: **Structure of the SEEA EA adapted from UN (2021) In red: the arrows highlight the entry point into the SNA, and the circle the asset definition we want to explore.**

Source: JRC.

The extent and condition accounts are structured as asset accounts and are compiled in physical terms only. Extent accounts measure the surface extension of different ecosystem types, such as cropland, grassland, woodland, and forests. Condition accounts estimate indicators on the health of ecosystems. While extent and condition accounts are structured as asset accounts, ecosystem services are structured as Supply and Use tables, where the supply table introduces the ecosystem types, and the use table reports the conventional economic units already in the SNA. Ecosystem services are first assessed in physical terms and then translated into monetary terms.

In this paper, we consider forest ecosystems. The wood extracted from the forest is the natural resource that enters the economic production function, standing timber is a natural asset, and the biomass growth that occurs as the net annual increment is the ecosystem contribution, i.e., the ecosystem service. Wood, as a natural resource that enters the production function, is visually summarized in Figure 2, where the asset account reports the resource stock at the beginning and at the end of the accounting period. The flows are generated by the stock in terms of addition (net annual increment) and subtraction (felling and removals).

Forests provide multiple services in addition to wood, such as carbon sequestration, flood

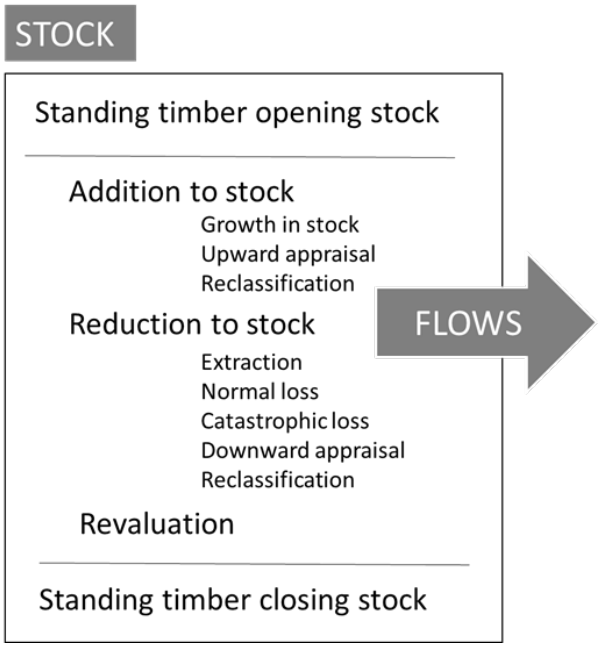


Figure 2: **Asset account for natural resource adapted from UN et al. (2014) meant to emphasize the "from stock to flow" directionality.**

Source: JRC.

mitigation, purification of water, maintenance of habitat and species, and nature-based recreation. The relationship between ecosystems and ecosystem services is from many to many (La Notte et al. (2019)) and the annual contribution of forest ecosystems is given by the sum of the services they provide (Figure 3). To move from the yearly flow to the concept of stock requires to calculate the Net Present Value, i.e. what can be provided (at least in principle) for its entire life span [1].

Several economic activities depend on forest services. The role of providing ecological inputs concerns almost entirely the forestry sector. The hazard aversion role of services affects transversally all economic activities that have their geographical location in areas exposed to the physical risks. The role of mitigating negative externalities involves those activities generating the externalities themselves. The rationale is that as long as forests can clean polluting substances then economic activities are enabled to continue with ongoing management practices. The role of forest ecosystem services such as carbon sequestration and maintenance of habitats and species is also considered in international agreements on climate change and biodiversity.

[1] Ref the SEEA EA chapter 10.3 in UN, 2021.

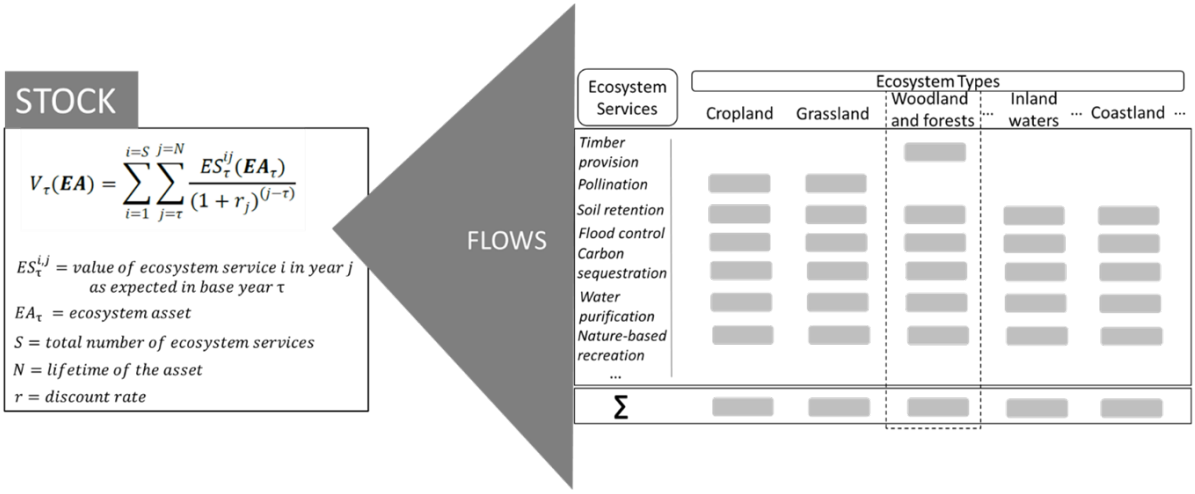


Figure 3: **Visual representation of how to move from the supply table of ecosystem services in monetary terms to the calculation of the ecosystem asset in monetary terms This image shows the "from flows to stock" directionality.**

Source: JRC.

3. DATA

Our analysis uses data from two distinct datasets provided by the World Bank and the European Commission. The World Bank dataset is sourced from the comprehensive wealth accounts (World Bank (2021)) offering global coverage from 1995 to 2018. Meanwhile, the European Commission dataset comprises data from the Integrated Natural Capital Accounting (INCA; Vallecillo et al. (2022) encompassing the EU-27 region for the years 2000, 2006, 2012, and 2018.

The World Bank data categorises natural capital into two broad groups: non-renewable and renewable resources. The latter refers to the value of forests, fisheries, mangroves, protected areas, cropland, and pastureland. Under the forest asset category, the dataset provides data for timber and non-timber ecosystem services (the latter as an aggregate value). The non-timber ecosystem services encompass a set of services, including cultural services like recreation, hunting and fishing, non-wood forest products, and watershed protection services. The assessment of the ecosystem services is grounded in a meta-regression analysis described in Siikamäki et al. (2021), which incorporates data from 53 countries across five continents. To estimate global spatially explicit predictions of different forest ecosystem services, variables related to socioeconomic factors, biophysics, climate, ecological extent, and ecological conditions were developed. The values are provided on a yearly basis in 2018 USD. In the present analysis, we specifically focus on the World Bank data pertaining to natural capital derived solely from renewable resources offered by forest assets.

The INCA dataset is constructed within the ecosystem accounting (EA) framework, a statistical framework for organising data, tracking changes in the extent and condition of ecosystems, measuring ecosystem services, and linking this information to economic and other human activities. INCA EA is based on the SEEA EA global standard (UN (2021b), where ecosystem services are measured in both biophysical and monetary terms. For the current analysis, we use the monetary values of ecosystem services provided by forest and woodland ecosystems in line with the EU ecosystem typology, and for four years at the country level. The data cover the following ecosystem services: wood provision, global climate regulation, flood control, water purification, habitat and species maintenance, and nature-based recreation. A summary of the biophysical models and the monetary valuation methods employed for each ecosystem service is provided in Annex A. Detailed descriptions are available in the different INCA reports: Vallecillo et al. (2018); Vallecillo et al. (2019) and La Notte et al. (2021).

The values originally refer to the flow of ecosystem service use (in constant 2015 euro) were produced in INCA 2018 (Vallecillo et al. (2022)). To align with the use of these values in the production function, we transformed the flows into stock values using the NPV approach, as in the World Bank report for forest ecosystem services (World Bank (2021)). Specifically, we assume an annual discount rate of 4% and a lifetime of the asset generating ecosystem services of 100 years. INCA ecosystem services data are compiled based on the biophysical assessment of services using spatially explicit models, providing good spatial resolution reflecting thus lower uncertainty in the value estimates. The data are produced within the INCA project and under the amended Regulation 691/2011[2] on European environmental economic accounts. The latest update completed under the INCA project pertains to the accounting year 2021 (Zurbaran Nucci et al. (2024)).

Table 1 summarises the various types of ecosystem services generated by the forest in each dataset. It also displays the mean value (and standard deviation) of each ecosystem service as a percentage of physical capital stock in 2018. While the values of timber provision are in line in the two datasets, INCA accounts for a greater number of non-provisioning ecosystem services. Thus, the average value and volatility are higher. Overall, we also note a lot of disparities across countries with respect to each ecosystem service and in both datasets.

In order to prepare data for the simulations presented in the next sections, we need to align

[2] The amended regulation has been approved by the Parliament and the Council but its publication is still pending. The law will mandate Member States to report on EA regularly and therefore ecosystem services accounting data will be produced annually starting in 2027.

Natural Capital Indicator	World Bank (global scale data)	European Commission (regional scale data)
Provisioning ecosystem services	Timber provision **2.11 (2.70)** Non-wood forest products	Wood provision **2.53 (2.40)**
Regulating and maintenance ecosystem services	Watershed protection	Global climate regulation **1.24 (1.43)** Flood control **1.08 (1.09)** Water purification **2.38 (3.86)** Habitat and species maintenance **5.30 (15.65)**
Cultural ecosystem services	Recreation, hunting, fishing	Nature-based recreation **2.54 (2.93)**
Forest asset	Total value of forest ecosystem services (excluding timber) **4.50 (3.30)**	Total value of forest ecosystem services (excluding wood provision) **12.55 (19.87)**

Table 1: **Natural capital indicators mean values in percent of physical capital**

Notes: This table compares the various types of ecosystem services that are accounted for in the WB and EC datasets. The mean EU value for 2018, in percent of physical capital, is reported in bold and the corresponding standard deviation in parentheses. Note that for World Bank data, we do not have the breakdown of ecosystem services other than timber.

the two datasets. For each EU country, we produce a set of variables in local currency and in real terms where the base year is 2015. To this end, we convert World Bank natural capital data using exchange rates and deflators from the World Bank. As for INCA data, we convert them to local currency using exchange rates from the AMECO database.

4. MODEL SETUP: ECOSYSTEM SERVICES IN A MACROECONOMIC PRODUCTION FUNCTION

Natural capital contributes to both market and non-market components of human well-being. Beyond its intrinsic value, ecosystems provide diverse benefits: tangible goods such as timber, fish, and fruits, which are traded in markets and valued through prices, as well as nonmarket services such as water purification, nutrient cycling, climate regulation, and cultural or recreational benefits. These latter services, while not exchanged through markets, directly support production and human welfare.

In this paper, we focus on forest-based ecosystem services, following recent approaches that emphasize both market (e.g. timber extraction) and non-market (e.g. carbon sequestration, recreation) contributions of natural capital to economic production. Our modelling framework is motivated by data availability and builds on earlier proposals to incorporate ecosystem services into aggregate production functions (see Dasgupta (2014); for empirical implementation, see Bastien-Olvera et al. (2023)).

We start with a standard constant-returns-to-scale Cobb-Douglas production function with manufactured capital K_t, labor L_t, and total factor productivity TFP_t:

$$Y_t = TFP_t L_t^{\alpha_1} K_t^{1-\alpha_1} \tag{1}$$

This benchmark form is widely used in macroeconomic projections (Havik et al. (2014); Guillemette and Turner (2021); ECFIN (2023)) and provides a transparent point of comparison for extensions that include natural capital.

To account for forest ecosystem services, we first extend equation (1) by introducing two components: market-based natural capital mN_t (e.g. timber) and nonmarket services S_t (e.g. regulation, recreation). This yields:

$$Y_t = TFP_t S_t^{\beta} L_t^{\alpha_1} K_t^{\alpha_2} mN_t^{1-\alpha_1-\alpha_2} \tag{2}$$

where β captures the contribution of nonmarket ecosystem services to output. This multiplicative form maintains a Cobb-Douglas structure and implicitly assumes an elasticity of substitution equal to one between all inputs, including ecosystem services. However, it does not exhibit constant returns to scale unless β = 0, meaning the introduction of nonmarket services alters the scaling properties of the function. We retain this formulation as a benchmark because it has been widely adopted in the recent literature, including the Dasgupta Review and related empirical applications.

To explore the implications of more flexible substitution patterns, we introduce a nested constant elasticity of substitution (CES) specification, which allows the elasticity of substitution between ecosystem services and other productive inputs to differ from unity:

$$Y_t = TFP_t \left(\omega S_t^{\frac{\sigma-1}{\sigma}} + (1-\omega)(L_t^{\alpha_1} K_t^{\alpha_2} mN_t^{1-\alpha_1-\alpha_2})^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \tag{3}$$

where ω = β/(1 + β) reflects the relative weight of ecosystem services, and σ denotes the elasticity of substitution. The CES formulation is homogeneous of degree one, since the input weights sum

to one, allowing for proportional scaling of all inputs. While it is not a literal generalization of the Cobb-Douglas form in equation (2), it allows us to relax the restrictive assumption of unitary substitution and examine the consequences of complementarity or substitutability between nature and conventional inputs.

The CES approach allows us to explore how different assumptions about substitution shape the macroeconomic role of ecosystems. When $\sigma < 1$, ecosystem services are complements to other inputs, and their degradation leads to disproportionately large output losses. Importantly, unlike in the Cobb-Douglas case, income shares are not constant over time or across scenarios, but evolve endogenously with relative input use and prices. This flexibility is critical for capturing the potential structural shifts arising from environmental constraints or conservation efforts.

To our knowledge, this nested CES specification has not yet been applied to ecosystem services in macroeconomic production functions[3]. We use it to simulate output dynamics under different ecological scenarios and degrees of substitutability, highlighting how structural assumptions affect macroeconomic outcomes.

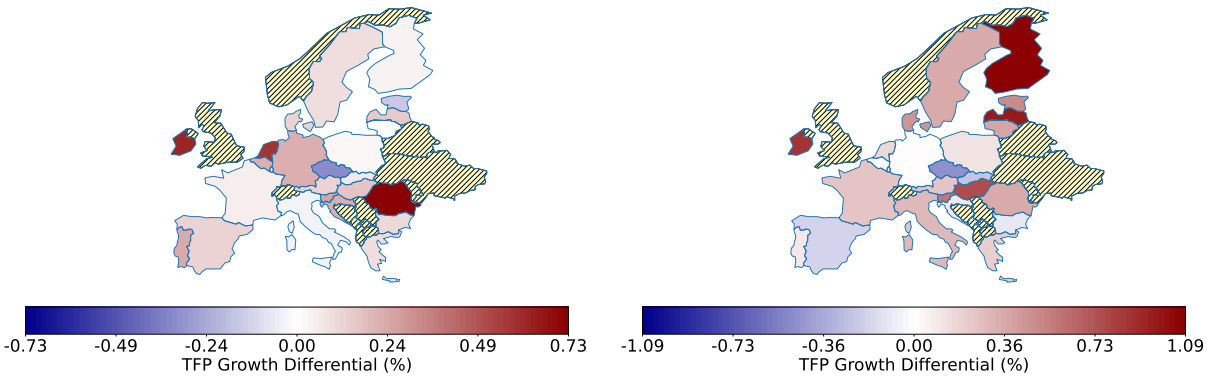
4.1. HISTORICAL TFP RECONSTRUCTION

In this section, we focus on the Cobb-Douglas production function (2) to reflect on the role of the ecosystem services. More specifically, we reconstruct historical TFP as Solow residual when the production process is augmented with natural capital and compare it with the one derived from the standard Cobb-Douglas (1). We take the estimated values of α_1 and α_2 from Bastien-Olvera et al. (2023). Regarding the share of regulating and maintenance services, β, we consider two different parameterisations. Bastien-Olvera et al. (2023) provide an estimation based on all global ecosystem services referring to S^{β} as "all the life maintaining mechanism of the Earth system". Focusing on global ecosystem services - such as climate regulation - as drivers of economic output in the EU highlights international interdependencies, but is a strong assumption. We therefore consider the $\beta = 0.15$ estimated by Bastien-Olvera et al as an upper bound to our simulations. For the illustration of a lower bound of ecosystem service contribution, we take forest ecosystem service flows in the EU-27 from the INCA database. They correspond to 0.97% of GDP in 2018. Assuming that this

[3] A growing literature has examined the role of substitutability between market and nonmarket goods, but primarily from the perspective of consumption or welfare analysis. For instance, Drupp and Hänsel (2021); Drupp et al. (2024); Heckenhahn and Drupp (2024) study how limited substitutability affects the relative price of ecosystem services and optimal climate policy through utility-based CES preferences. On the production side, Benmir et al. (2025) develop a richer macroeconomic model with multiple types of natural capital and empirically estimate CES elasticities, but their framework differs substantially in structure and scope from the simpler nested CES specification adopted here.

would be forest ecosystem's income share if they were marketed under full competition, this gives us an alternative value of $\beta = 0.01$. Rather than global ecosystem services, S^{β} in this alternative setup represents only forest ecosystem services, and the geographical scope is limited to the EU-27 without any consideration of international spillovers beyond Europe.

The maps in Figure 4 (with $\beta = 0.15$) and Figure 5 (with $\beta = 0.01$) present a visual representation of the relevance of natural capital into production processes. Figure 4a and Figure 5a are produced using WB data, while Figure 4b and Figure 5b are produced using INCA data. We compute the TFP growth differential for each Member States where blue colours, with different intensities, refer to the cases in which the average TFP growth recomputed considering the role of natural capital into production processes is lower than the historical TFP growth corresponding to the Solow residual of eq. (1).



(a) Average yearly TFP growth differential across EU ($\beta = 0.15$) from 2000 to 2018 using World Bank data.

(b) Average yearly TFP growth differential across EU ($\beta = 0.15$) from 2000 to 2018 using European Commission data.

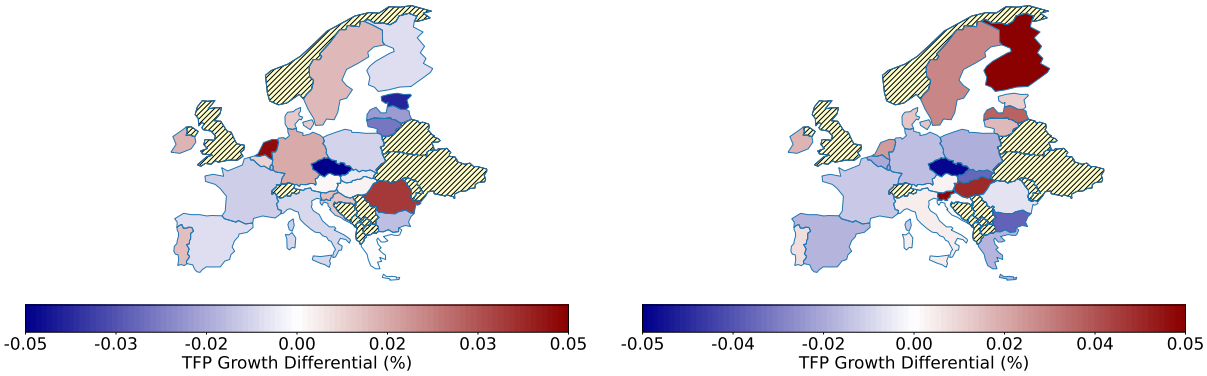
Figure 4: **Comparison of TFP growth differentials using World Bank and European Commission data.**

Notes: We compute the TFP growth differential as the difference between log TFP growth in the baseline case and log TFP growth in the Cobb-Douglas case with ecosystem services. A positive value implies that part of the TFP measured in the baseline case can be attributed to ecosystem services.

Source: Own calculations.

The maps suggest that, in the majority of countries, natural capital contributes positively to economic growth, although with different intensities, with some European countries, like Romania and Ireland, more heavily influenced by natural capital. Interestingly, some countries (and in particular Czech Republic consistently across all specifications) exhibit a higher TFP growth using the baseline production function. This means that these countries' GDP growth has been impacted negatively by the evolution of the stock of natural capital.

Overall, the two datasets yield quantitatively comparable results. While the two maps present some heterogeneity, they document a common role for natural resources and services across EU countries, with the exception of few countries. It is also worth noting that using a lower β implies a smaller impact of natural capital but does not impact results qualitatively.



(a) Average yearly TFP growth differential across EU (β = 0.01) from 2000 to 2018 using World Bank data.

(b) Average yearly TFP growth differential across EU (β = 0.01) from 2000 to 2018 using European Commission data.

Figure 5: **Comparison of TFP growth differentials using World Bank and European Commission data**

Notes: We compute the TFP growth differential as the difference between log TFP growth in the baseline case and log TFP growth in the Cobb-Douglas case with ecosystem services. A positive value implies that part of the TFP measured in the baseline case can be attributed to ecosystem services.

Source: Own calculations.

In this section, we focus on EU Member States in view of being able to compare the implications of the two datasets. An interesting extension could be to look also at countries outside the EU –mostly lower and middle income countries– that have a higher share of their wealth in –renewable– natural capital.

4.2 POTENTIAL OUTPUT PROJECTIONS

We now focus on potential output scenarios to assess the relevance of natural resources and services and their degradation in the medium term. Our benchmark is the production-function approach (eqn. (1)) employed in the European Commission's Ageing Reports (ECFIN (2023)), from which we take the projections for fixed capital, labour and TFP at the country level. Given these projections, potential output is extended for 60 years using the perfect foresight method described in Annex B.

At the country level, the effect of the degradation of natural capital on potential output is assessed by the CES production function:

$$Y_{c,t} = TFP_{c,t}\left(\omega S_t^{\frac{\sigma-1}{\sigma}} + (1-\omega)(L_{c,t}^{\alpha_1} K_{c,t}^{\alpha_2} m N_{c,t}^{1-\alpha_1-\alpha_2})^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \quad (4)$$

where, unlike all other region-specific production factors, the environmental good S is considered a global production input providing maintenance and regulation services usable regardless the national economy in which it is embedded[4]:

$$S_t = \sum_c S_{c,t} \quad (5)$$

As in the previous sub-section, we also consider the alternative case where the scope of Sis limited to forest ecosystem services in the EU.

We also assess the impact of natural capital degradation using a Cobb-Douglas production function (eqn.(2)): a particular case of a CES where the elasticity of substitution σ equals 1. In this special case, the drop in output caused by the reduction of ecosystem services corresponds to ΔlogY = βΔlogS. However, when ecosystem services are critical to production, the elasticity of substitution must be strictly lower than 1. In the extreme case of σ = 0, ecosystem services are a bottleneck and the drop in output is proportional to the drop of S. In our illustration of the impact of limited substitutability we assume an elasticity of substitution of 0.9 and 0.6.

In order to simulate climate-change induced projections for market and non-market ecosystem benefits, we follow Bastien-Olvera et al. (2023) and use trajectories of country-level natural capital stocks under climate-change-driven biome range shifts as projected by dynamic

[4] We are aware that this assumption may be less realistic for specific ecosystem services. While in our simple framework we do not distinguish among different types of ecosystem services, future extensions could explore different roles and characteristics of specific ecosystem services.

global vegetation models (DGVMs) driven by general circulation climate models. This implies that marketed and non-marketed natural capital are projected from 2018 till 2085 using the damage function:

$$x_{c,\tau+k} = x_{c,\tau}(1 + \theta^{c,x}\Delta t_k)$$

where τ = 2018 is the last year for which data on natural capital are available, x = (mN, S), $\theta^{c,x}$ is a the country specific damage coefficient, and Δt is the change in temperature as prescibed by the Shared Socioeconomic Pathway scenarios SSP1 or SSP5. Under SSP1, global warming is contained well below 2 degrees Celsius, whereas SSP5 is an extreme scenario of very high greenhouse gas emissions associated with an expected global mean temperature increase of 4.4 degrees by the end of the century (see Lee et al. (2021))[5].

	2050			**2085**		
	$cd(\beta)$	$ces(\beta, 0.9)$	$ces(\beta, 0.6)$	$cd(\beta)$	$ces(\beta, 0.9)$	$ces(\beta, 0.6)$
$\beta = 0.01$						
SSP1	0.10	0.12	0.72	0.18	0.27	2.23
SSP5	0.10	0.13	0.84	0.21	0.33	3.13
$\beta = 0.15$						
SSP1	0.20	0.46	1.22	0.54	1.35	3.50
SSP5	0.25	0.52	1.42	0.88	1.85	4.85

Table 2: **EU-25 output loss w.r.t the baseline (trillion euro)**

Notes: cd denotes the extended Cobb-Douglas production function (eq. 2), ces(σ) denotes the CES production function with σ as elasticity of substitution (eq. 3), SSP: Shared Socioeconomic Pathway, SSP1 and SSP5 are the temperature scenarios where projected temperature increases the less and the most respectively.

Table 2 shows the economic damages stemming from different scenarios on degradation of ecosystem services and different substitutability of ecosystem services in the production function. Losses are reported at the aggregated level: the EU member states excluding Cyprus and Malta. Annex C shows deviations from the baseline scenario at the country level. The table presents both results related to degradation of global ecosystem services (β = 0.15) and to the case when only the ecosystem services from EU forests are considered (β = 0.01). In the latter case, with unity elasticity of substitution and the more conservative natural capital degradation scenario, the output loss with respect to the projections related to the baseline methodology is estimated to reach around 100

[5] Figure 8 illustrates the two pathways considered in the analysis.

bn euro in bn euro in 2085 (around three quarters of a percent of EU GDP). Considering a more severe degradation of ecosystem services, the economic damage in the EU would reach around 210 bn euro in 2085. When global ecosystem services are considered, and not just services from EU forests, losses could reach 250 bn euro in 2050 and almost 900 bn euro in 2085 (roughly 3.5% of EU GDP) in the severe degradation scenario. This is substantial given that we look only at ecosystem services. In fact, previous estimations of total climate damages to the EU amid moderate global warming were often in the same range (Feyen et al. (2020), Hope (2011), COACCH (2021)).

Considering the possibility of limited substitutability of ecosystem services changes the picture dramatically. Although we know too little about the true elasticity of substitution, our illustrative numerical values are quite striking. We observe that considering only ecosystem services of EU forests, moving from $\sigma = 1$ to $\sigma = 0.9$ increases the simulated economic damages by 20% and that with $\sigma = 0.6$ they reach more than 700 bn in 2050 and more than 2 trillions in 2085 in the conservative degradation scenario. The severe scenario losses are uniformly larger. The high sensitivity on the assumed elasticity of substitution demonstrates the need for increased research efforts on substitutability. When global ecosystem damages are simulated, $\beta = 0.15$, the economic damages become even more relevant.

We provide an additional synthetic figure to illustrate the overall lower and upper bound of the level of EU potential output projections in the various scenarios considered in Table 2. Figure 6 provides the potential output projections of the baseline approach and compares it with the envelop of projections obtained according to all settings reported in Table 2. The figure clearly illustrates the wide spectrum of the envelop. Indeed, potential output figures deteriorate dramatically in the least favourable scenario assumed in our analysis (limited substitutability and severe global ecosystem services degradation), according to which potential output is estimated to reach only around 16.5 trillions euro in 2050 and barely 20 trillion in 2085 implying an economic damage of roughly 5 trillion in 2085.

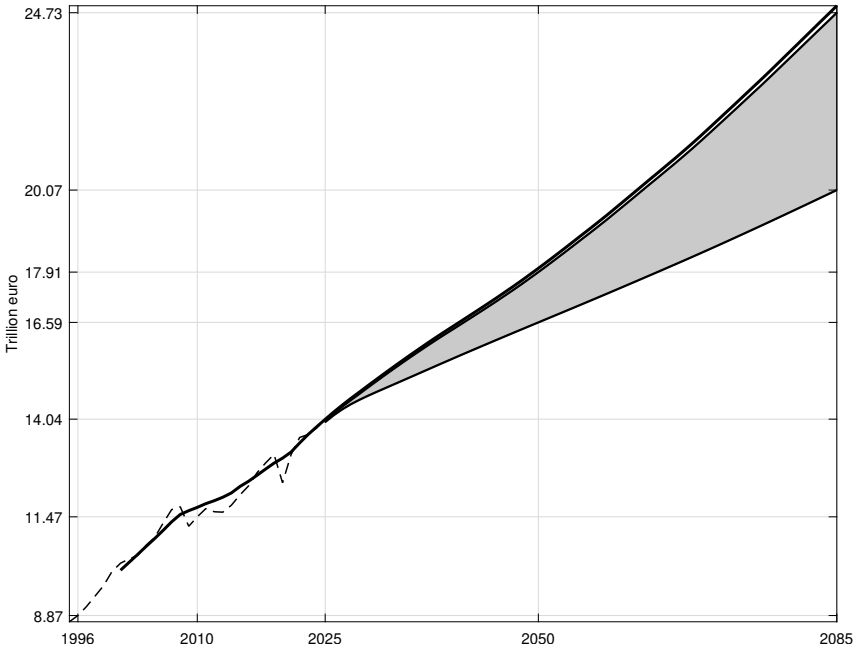


Figure 6: **EU potential output deviations w.r.t. the baseline**

Notes: GDP (dashed line), baseline potential output (tick line), Lower and Upper bound across scenarios (extremes of the shaded area).

Source: Own calculations.

The variability of the percentage deviations of potential output projections from baseline across Member States is summarised in figure 7. The boxplots relate to ecosystem degradation scenarios and production function elasticities assumed in Table 2. In order to better appreciate the variability of results the boxplots refer to the global ecosystem service degradation ($\beta = 0.15$). Not surprisingly, limiting substitutability of ecosystem services implies higher median percentage losses. These reach up to 8% in 2050 and to more than 10% in 2085 in the least substitutable case. In the worst degradation scenario, the median loss could reach more than 15% in 2085. Lower substitutability is also accompanied by higher dispersion across countries.

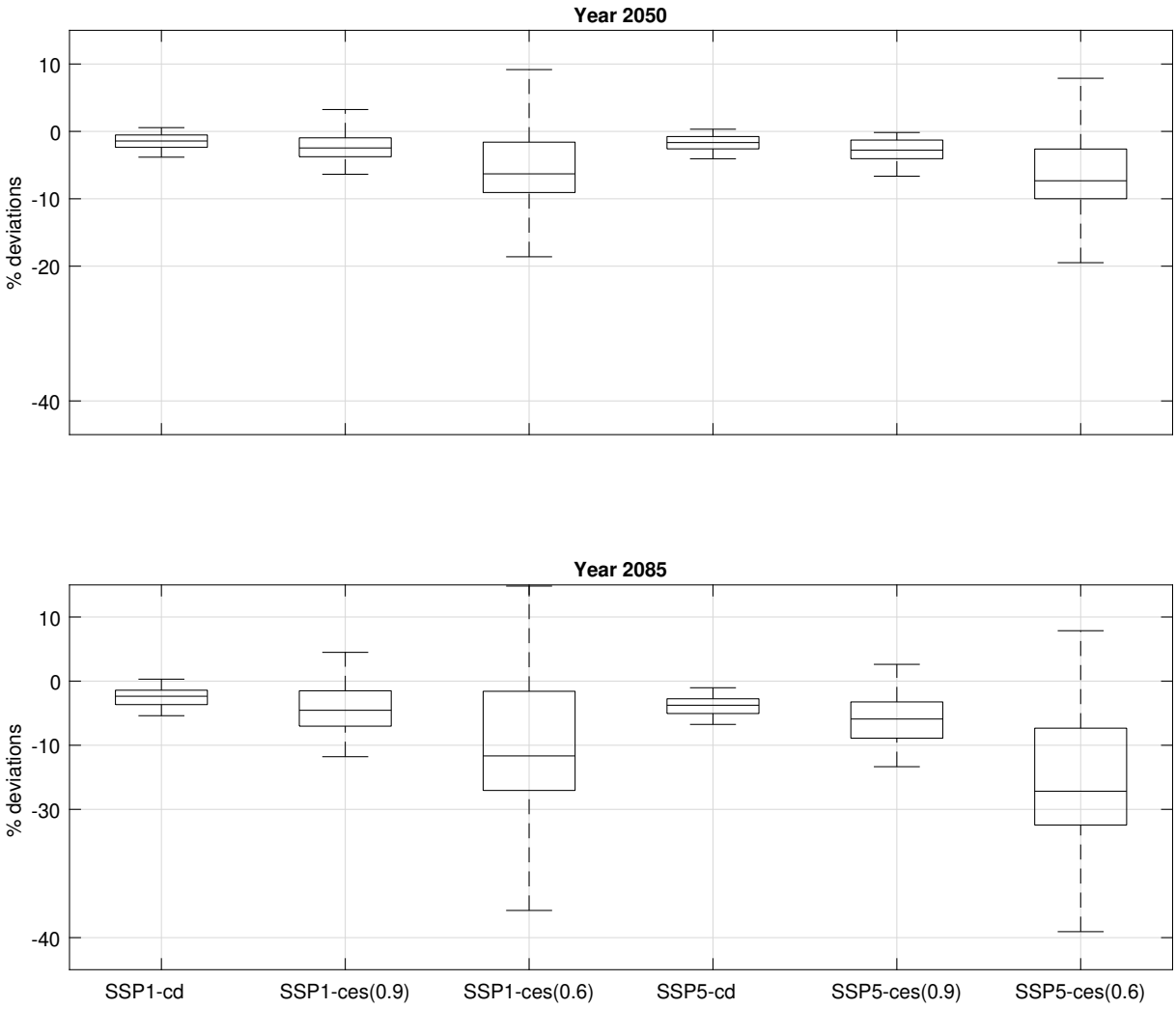


Figure 7: P**otential output deviations w.r.t. the baseline**

Notes: On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers. cd denotes the extended Cobb-Douglas production function (eq. 2), ces(σ) denotes the Constant Elasticity of Substitution production function where σ is the elasticity parameter (eq. 3), SSP: Shared Socioeconomic Pathway, SSP1 and SSP5 are the temperature scenarios where projected temperature increases the least and the most respectively.

Source: Own calculations.

5. CONCLUSIONS AND ISSUES FOR FURTHER RESEARCH

This paper explores the contribution of ecosystem services to the economy first conceptually and then quantitatively, focusing on forests. The wood that is extracted from forests is a marketed renewable asset; the growth of tree biomass is a provisioning service provided by the forest ecosystem. Simultaneously, forests provide regulating, maintenance and cultural services on which economic activity also depends. Economic activities in turn generally rely on services provided by several different ecosystems. We use forest ecosystem services data in a fairly simple macroeconomic production function framework to demonstrate its suitability for studying the dependence of the economy on natural assets. We use this framework to simulate different paths for the future dynamics of forest ecosystems to assess how these might impact economic production possibilities in the coming decades.

When we simulate the long-term impact of declining ecosystem services, we find sizeable impacts between 0.7 and 2 percent of EU GDP even in a scenario with ambitious climate mitigation policies. This is an order of magnitude that is found in some projections of total climate damages whereas we only cover the decline of ecosystem services. Our setup with non-marketed global ecosystem services can be considered a plausible upper bound, whereas by restricting the scope of ecosystem services to those provided by forests within the EU, we obtain a lower bound. As we are particularly interested in the consequences of limited substitutability between natural and man-made inputs, we then extend our framework to allow different assumptions on the elasticity of substitution. Assuming that ecosystem services can only to a limited degree be replaced by fixed assets or labour, the negative impact of their degradation on economic output could become large. In view of the uncertainty about the actual elasticity of substitution, our numerical simulations should however be seen as illustrative, and our analysis as a proof of concept.

There are several ways to extend our analysis. A first step would be to use the more disaggregated ecosystems data from the INCA project to study the relative role of different forest ecosystem services. Second, our narrow focus on forest ecosystems is largely driven by limited data availability for other ecosystems. As the statistical coverage of ecosystem services improves, our approach could be generalised. Thirdly, the strong sensitivity of our results on the assumed elasticity of substitution points to the need for further work on substitutability. Finally, studying the bio- physical underpinnings of ecosystem dynamics (in particular use,

depletion, natural regeneration and stability) would allow basing our scenarios on explicit accumulation equations for natural capital instead of climate-related damage functions. Ideally, by also including the impact of pollutants on ecosystem dynamics, the feedback loop between economic activity, damages to ecosystems and consequences for economic prospects could be closed.

A Biophysical and monetary valuation methods employed for each ecosystem service

Wood provision: the biophysical assessment of this service relies on official statistics and not models, because most European forests are managed. Wood provision refers to the production of woody biomass by the forestry sector, and only forest land designated as available for wood supply is considered to determine the actual flow. Consequently, the estimates reported are limited to the woody biomass in Forests Available for Wood Supply (FAWS) and are expressed in cubic meters (m^3) of woody biomass. By applying the market price technique to the estimated quantity in biophysical terms, it is possible to translate the ecosystem service flow into monetary terms.

Global climate regulation: carbon (C) sequestration is used as a proxy to estimate this ecosystem service. Specifically, the INCA approach focuses on CO2 uptake from the atmosphere into forest land, according to the Land Use, Land Use Change and Forestry definition (LULUCF). The biophysical mapping is based on LULUCF inventories, which provide annual estimates of CO2 emissions and removals resulting from direct human-induced activities related to land use, land use changes, and forestry. The difference between the CO2 captured by the ecosystem and its emissions corresponds to the ecosystem service flow, which is expressed in $tCO2/km^2$. The monetary evaluation applies the market price method, considering a price of EUR 30 per tonnes of CO2.

Flood control: the biophysical assessment is based on the existing spatial relationship between service providing areas (SPA) and service demanding areas (SDA). Therefore, the use of the service is quantified for each grid cell of the SDA where there is a demand for flood control. The biophysical assessment of this ecosystem service is expressed in hectares (ha) of the demand (SDA) covered by the ecosystem (SPA) in a year. The ES flow of flood control is translated into monetary terms using the avoided damage cost technique. The damage function provides the damage cost, expressed in EUR/m^2, as a function of the water depth in the flooded area for each damage class (buildings, commerce, industry, roads, and agriculture). The damage function is based on the Gross Domestic Product (GDP) per capita of countries, with prices considered as fixed.

Water purification: the water system's capacity to remove nitrogen is used as a proxy to quantify this ecosystem service. The biophysical assessment is based on the GREEN model

(Geospatial Regression Equation for European Nutrient losses), a statistical model that estimates the flow of nitrogen and phosphorus inputs into surface water of large river basins. The flow has been reprocessed to reflect its deviation from a sustainable nitrogen load, and it is expressed in tonnes of nitrogen retained per hectare (t N/ha). The method applied to assess the water purification service in monetary terms is the replacement cost. The replacement cost estimates are calculated based on the area of constructed wetlands needed to remove the same amount of nitrogen that is removed within each sub-catchment.

Habitat and species maintenance: the biophysical assessment of this ecosystem service is based on the relationship between two factors: the presence of suitable ecological conditions (identified as suitable habitat) and the presence of species hotspots. The first factor is represented by an ad hoc indicator called the habitat suitability indicator, which identifies suitable habitats for supporting species populations. The second factor is the bird species richness hotspots indicator, which is used to identify species hotspots. The monetary evaluation applied is the state preference method, an ad hoc choice experiment questionnaire has been developed to obtain the respondent willingness to pay and their preferences for different habitat and species maintenance policies.

Nature based recreation: the ES flow is based on the spatial relationship between areas that offer opportunities for daily recreation, known as service providing areas (SPA), and the people who demand outdoor recreation activities. For practical reasons, the flow only considers the fraction of the population living within 4 km of the SPA, and it is expressed in terms of the number of visits per square kilometer per year (visits/km^2/year). Nature based tourism service is evaluated in monetary terms using the revealed preference technique, the travel cost method. By analyzing travel expenditures and the number of trips, it is possible to estimate the monetary value of the daily outdoor recreation service.

B Overview of the methodology

This annex gives a brief overview of the methodology used in the paper. The approach taken follows closely the European Commonly Agreed Methodology (EUCAM) for estimating potential output and output gap for what concerns total factor productivity, manufactured capital and labour. An exhaustive description of EUCAM can be found in Havik et al. (2014). Given yearly observations until time T (2023) plus additional two-year-ahead forecasts for all input variables that come from the European Commission's Autumn Economic Forecasts, potential output and output gap are first estimated until time T+2 as explained in next section. These results are then used to build long-term forecasts from T+3 to 2085 using a simultaneous system of equations which is discussed afterward.

Potential output scenarios are produced using three distinct production functions: (i) a standard Cobb-Douglas without natural capital (baseline), (ii) an extended version of the latter which features both marketed and non-marketed natural capital as in Bastien et. al. (2003), (iii) a CES production function where non-marketed natural capital and the remaining production factors exhibits some degree of substitutability.

B.1 Potential output until T+2: baseline

The benchmark model is represented by a Cobb-Douglas technology where output Y is produced by labour L, physical capital K, and total factor productivity TFP as in:

$$Y_t = TFP_t \; L_t^{\alpha} \; K_t^{1-\alpha} \qquad \text{with } \alpha = 0.65 \tag{B.1}$$

Here, natural capital is not among the input factors. Potential output YP is determined by potential total factor productivity TFPP, potential labour LP, and capital according to:

$$YP_t = TFPP_t \; LP_t^{\alpha} \; K_t^{1-\alpha} \tag{B.2}$$

The output gap YG, in percentage points (pp), relates potential GDP to actual GDP as in:

$$Y_t = YP_t(1 + YG_t/100)$$

B.1.1 Labour

Labour is measured in terms of hours as the product of hours worked per employee hpere times the number of employees *empl*:

$$L_t = hpere_t \times empl_t \tag{B.3}$$

Potential labour, LP, equals the product of the hours worked trend, hperehp, times the employment trend emplp:

$$LP_t = hperehp_t \times emplp_t \tag{B.4}$$

The trend in hours worked is calculated using the HP filter with an inverse signal to noise ratio λ set equal to 10, after extending the series from T+3 to T+8 using an autoregressive model. To obtain the employment trend (pp), the total number of employees is first decomposed into the working age population popw, the participation rate (pp) part, and the rate of employment, or equivalently one minus the harmonized rate of unemployment 1 − lurharm$_t$/100:

$$empl_t = popw_t \times (part_t/100) \times (1 - lurharm_t/100) \tag{B.5}$$

The potential number of employees verifies:

$$emplp_t = popw_t \times (parts_t/100) \times (1 - nawru_t/100) \tag{B.6}$$

where parts denotes the trend in participation rate and nawru the non-accelerating wage inflation rate of unemployment. The trend in participation rate is calculated using the HP filter with an inverse signal to noise ratio λ = 10 after extending the series from T+3 to T+8 using an autoregressive model. The participation rate is obtained by inverting (B.5). The trend unemployment rate is calculated as an anchored NAWRU (see Hristov et al. (2017)). In a first step the unemployment rate is decomposed in a trend and a cycle

which are assumed to evolve stochastically as in:

$$\begin{aligned} lurharm_t &= nawru_t + c_t \\ nawru_t &= nawru_{t-1} + \eta_{t-1} + a_{nt} \\ \eta_t &= \eta_{t-1} + a_{\eta t} \\ c_t &= \phi_{c1} c_{t-1} + \phi_{c2} c_{t-2} + a_{ct} \end{aligned} \tag{B.7}$$

The trend component follows a second-order integrated process without level shocks. The cyclical component of unemployment is related to a labour cost indicator w through the Phillips curve equation:

$$w_t = \mu_w + \phi_{w1} w_{t-1} + \beta_0 c_t + \beta_1 c_{t-1} + \gamma_w' z_t + a_{wt} \tag{B.8}$$

All shocks a_{nt}, a_{nt}, a_{ct}, and a_{wt} are independent and normally distributed white noises. The vector z_t contain the second difference of exogenous variables such as labour productivity, terms-of-trade, and the wage share. In a second step the NAWRU is corrected to incorporate an anchor A to which it is assumed to converge at some horizon T + h under the hypothesis of no-policy change; in short it is assumed that $nawru_{T+h} = A_{T+h}$, where h is typically equal to ten years (Hristov et al. (2017)). The anchor is built using a panel regression on structural indicators of the labour market (Hristov and Roeger (2020)). Plugging the NAWRU estimates together with the working age population and the smoothed participation rate into (B.4) yields potential labour up to T+2.

B.1.2 Physical Capital

The net capital stock is calculated using the Perpetual Inventory Method. Capital stock grows through real gross fixed capital formation IQ and it decreases with the consumption of capital CF C. Given the investment deflator defl and a starting point in 1960, real capital stock K is measured as:

$$K_t = K_{t-1} + IQ_t - \frac{CFC_t}{defl_t} \tag{B.9}$$

Two-year-ahead forecasts are provided by the country-desks in DG ECFIN. Capital contributes entirely to potential output and it is not subject to any transformation.

B.1.3 Total Factor Productivity

TFP is calculated by exponentiating the Solow residual sr_t defined by:

$$sr_t = \log Y_t - \alpha \log L_t - (1-\alpha) \log K_t \tag{B.10}$$

Two-year-ahead forecasts of the Solow residual are provided by the country-desks in DG ECFIN as part of the European Economic Forecasts. The Solow residual including the two-year-ahead extension is then decomposed into a trend srk plus a cycle c using the model:

$$\begin{aligned} sr_t &= srk_t + c_t \\ srk_t &= srk_{t-1} + \mu_p + \eta_{t-1} + a_{pt} \\ \eta_t &= \rho \eta_{t-1} + a_{\eta t} \\ c_t &= 2\ Acos(2\pi/\tau) c_{t-1} - A^2 c_{t-2} + a_{ct} \end{aligned} \tag{B.11}$$

The trend component srk follows a damped trend model with average growth μ_p. The cyclical component c follows instead a second-order autoregressive process which is parameterized in terms of amplitude A and periodicity τ. The productivity cycle also appears in the fluctuations of capacity utilization, cubs, so the model is completed with the measurement equation:

$$cubs_t = \mu_{cu} + \beta_{cu} c_t + e_t$$

$$e_t = \phi_{cu} e_{t-1} + a_{cut} \tag{B.12}$$

where e_t is an unobserved idiosyncratic component which can be autocorrelated. All shocks, namely a_{pt}, a_{nt}, a_{ct}, and a_{et} are independent and normally distributed white noises. The cubs indicator is built from capacity utilisation surveys in industry and two economic sentiment indicators for construction and services. Contrary to the Solow residual, no T+2 forecasts are available for cubs which ends in time T or sometimes earlier. To cope with this the estimation procedure allows for missing observations.

Model (B.11)-(B.12) is estimated in the Bayesian framework given prior distributions for each EU Member State. Given the prior distributions, the Solow residual, and the capacity utilisation series, the trend component srk_t is estimated by its posterior mean in a Bayesian inference as

explained in the GAP Manual. The estimate of potential TFP is then obtained as:

$$TFPP_t = \exp(srk_t) \tag{B.13}$$

Plugging potential TFP (B.13), potential labour (B.4), and capital into (B.2) yields potential GDP up to T+2.

B.2 Potential output until T+2 with the extended CD and CES production function

The treatment of labour and physical capital follows exactly the same step described earlier. The Solow residuals sr^{cd} and sr^{ces} are computed as follows:

$$sr_t^{cd} = \log Y_t - \beta S_t - \alpha_1 \log L_t - \alpha_2 \log K_t - (1 - \alpha_1 - \alpha_2) log(mN_t) \tag{B.14}$$

where S and mN are non-marketed and marketed natural capital.

$$sr_t^{ces} = \log Y_t - \frac{\sigma}{\sigma - 1} log \left(\omega S_t^{\frac{\sigma-1}{\sigma}} + (1 - \omega)(L_t^{\alpha_1} K_t^{\alpha_2} mN_t^{1-\alpha_1-\alpha_2})^{\frac{\sigma-1}{\sigma}} \right) \tag{B.15}$$

Since data on marketed and non-marketed natural capital from the WB database are available until 2018, S_t and mN_t, t = 2019, $\cdots$, 2025, are computed as in Bastien et al (2023). More details are given in the sequel

B.3 Long-term forecasts: from T+3 to 2085

Potential output projections are obtained using the following system of non-linear equations:

$$\begin{aligned}
YP_t &= g(TFPP_t,\ LP_t,\ K_t,\ mN_t,\ S_t; \Psi) \\
K_t &= IQ_t + (1 - \delta_t)\ K_{t-1} \\
IQ_t &= (IYP_t/100)\ YP_t \\
Y_t &= YP_t\ (1 + YG_t/100) \\
TFP_t &= Y_t / g(1,\ LP_t,\ K_t,\ mN_t,\ S_t; \Psi)
\end{aligned} \tag{B.16}$$

where g(·) is either the standard Cobb-Douglas, the extended Cobb-Douglas with natural capital, or the CES production function depending on the model used. The elasticities are collected in the vector Ψ. Given inputs from T F P P , LP , δ, IY P , Y G, S, and mN the model above yields long-term projections for potential output Y P using the recursive method discussed in Juillard (1996). The path taken by these projections depends on the elasticities and the extensions assumed for some exogenous variables that enter system (B.16). These extensions are described in the next section.

B.3.1 Extension of the exogenous variables from T+3 to 2085

Potential TFP is extended assuming that trend TFP growth rate converges to 0.8 pp in the long run for all countries as stated in ECFIN (2023) as follows

$$srk_{t+k} = 0.008 + 0.4^{k}(srk_t - 0.008)$$

Projections of potential labour LP depend on several variables (see (B.4)-(B.6)). Total population and working age population are taken directly from Eurostat. The NAWRU is first extended from T+3 to T+10 by setting it to the estimates described by the system given in (B.7)-(B.8). From T+11 to 2085 it is assumed to be constant and equal to the (country specific) structural unemployment A. The participation rate of the working-age population is projected to increase by around 3 pp from 2025 to 2085 as in ECFIN (2023). Trend hours worked declines of 9 pp between 2025 and 2085 as predicted in ECFIN (2023).

The physical Capital depreciation rate, δ, is set constant to the last in-sample value from T+3 till 2085.

Investment to potential ratio, IY P , is extended till 2085 using an autoregressive model.

The output gap is extended from T+3 till 2085 by assuming that it closes (goes to zero) in three years.

Non-marketed and marketed natural capital are projected from T+3 to 2085 using the damage function in Bastien et. al. (2023):

$$x_{\tau+k} = x_{\tau}(1 + \theta^{x}\ temp_k)$$

where τ = 2018, x = (mN, S), θ^{x} is country specific, and temp is temperature changes in the Shared Socioeconomic Pathway scenarios SSP1 or SSP5 as shown in figure B1. The coefficient θ^{mK} and θ^{S} for the EU-25 countries considered in our exercise can be found in the supplemental material to

Bastien et. al (2023).

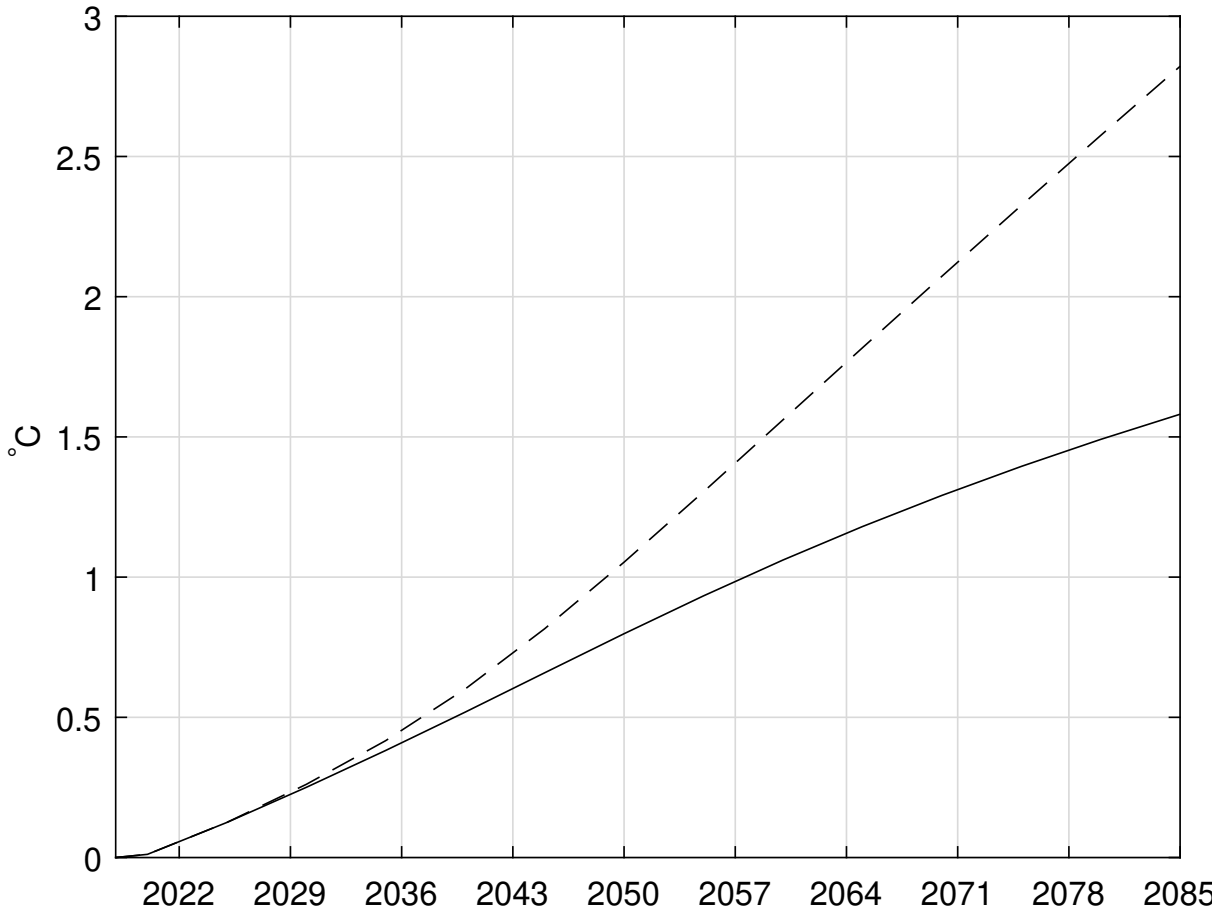


Figure 8: **Temperature changes in scenarios SSP1 and SSP5 (dashed)**

Notes: Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to 2100 as defined in the IPCC Sixth Assessment Report on climate change in 2021. Deviations from 2018.

C Potential output deviations from baseline at the country level

Table C1 shows potential output deviations (pp) from baseline scenario for the years 2050 and 2085 for all EU member states, excluding Cyprus and Malta, assuming $\beta = 0.15$. The case $\beta = 0.01$, not reported, exhibits a similar patterns for the deviations but with a smaller magnitude.

Table C1. **Potential output deviations relative to baseline (%)**

	2050						2085					
	SSP1			SSP5			SSP1			SSP5		
	cd	ces(.9)	ces(.6)	cd	ces(.9)	ces(.6)	cd	ces(.9)	ces(.6)	cd	ces(.9)	ces(.6)
AT	-2.6	-4.9	-9.8	-2.7	-5.1	-10.5	-4.4	-9.6	-19.5	-5.1	-10.9	-22.7
BE	-0.8	-4.9	-12.4	-1.0	-5.4	-13.7	-1.7	-10.1	-23.4	-3.3	-12.9	-29.2
BG	-1.3	-2.2	-5.4	-1.8	-3.2	-8.2	-3.9	-4.6	-10.3	-7.2	-10.4	-24.6
CZ	-1.0	-2.9	-8.0	-1.3	-3.3	-9.4	-2.7	-7.0	-17.8	-4.4	-9.6	-24.5
DE	-2.4	-3.3	-6.0	-2.7	-3.8	-7.5	-4.6	-8.4	-16.8	-6.2	-11.3	-23.5
DK	2.4	-0.4	-6.7	2.3	-0.5	-7.2	3.0	-2.8	-13.8	2.4	-3.7	-16.1
EE	-1.1	-3.6	-7.6	-1.0	-3.4	-7.2	-1.4	-5.1	-10.4	-1.0	-4.5	-8.8
EL	0.5	4.2	11.3	0.3	3.9	10.4	-1.1	6.6	19.3	-1.9	5.1	14.4
ES	0.3	-2.1	-7.2	0.1	-2.5	-8.3	-0.1	-3.9	-11.3	-1.3	-6.0	-16.5
FI	-3.4	-4.8	-8.9	-3.6	-5.1	-10.1	-5.5	-6.8	-11.5	-6.7	-8.8	-17.1
FR	-0.5	-2.4	-6.5	-0.6	-2.7	-7.3	-1.1	-5.9	-14.6	-2.1	-7.5	-18.3
HR	-1.0	-1.1	-3.0	-1.4	-1.8	-4.9	-2.9	-1.8	-3.8	-5.0	-5.6	-13.5
HU	-1.9	-4.3	-11.8	-2.3	-4.9	-13.8	-4.2	-8.3	-21.3	-6.8	-11.8	-30.5
IE	-1.4	-8.3	-20.3	-1.7	-8.9	-21.9	-3.3	-13.9	-30.5	-5.6	-17.4	-37.5
IT	-0.5	0.3	1.4	-0.6	-0.0	0.5	-1.1	0.3	1.4	-2.0	-1.4	-3.1
LT	-1.8	-0.4	2.9	-1.8	-0.3	3.2	-2.0	5.7	21.4	-1.7	6.3	23.1
LU	-4.6	15.0	–31.8	-5.0	-15.	-33.4	-7.3	-24.3	-46.8	-9.7	-27.9	-53.2
LV	-1.4	1.6	8.4	-1.4	1.6	8.5	-1.7	6.2	22.4	-1.6	6.3	22.9
NL	-1.9	-5.3	-12.2	-2.3	-6.1	-14.1	-3.8	-11.2	-23.6	-6.1	-15.3	-32.2
PL	-2.0	-3.8	-7.4	-2.1	-4.0	-7.9	-3.0	-2.8	-3.5	-3.6	-4.0	-6.5
PT	-3.1	-1.4	0.2	-3.5	-2.1	-1.6	-5.7	-3.8	-4.4	-7.7	-7.4	-13.7
RO	-2.8	-4.0	-3.2	-3.1	-4.4	-4.5	-4.4	-4.7	-3.9	-5.8	-7.1	-10.3
SE	-1.9	-7.8	-22.1	-2.3	-8.2	-23.6	-3.4	-14.7	-37.8	-5.4	-17.4	-43.8
SI	-4.0	-5.9	-11.1	-4.4	-6.7	-13.2	-6.5	-10.3	-20.1	-9.2	-14.8	-30.2
SK	-2.5	-3.8	-6.5	-2.7	-4.2	-7.5	-3.7	-3.1	-4.3	-4.9	-5.3	-9.6

Notes: cd denotes the extended Cobb-Douglas production function (eq.(2)), ces(σ) denotes the Constant Elasticity of Substitution production function where σ is the elasticity parameter (eq.(3)), SSP: Shared Socioeconomic Pathway, SSP1 and SSP5 are the temperature scenarios where projected temperature increases the less and the most respectively.

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